TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

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SUMMARY OF PH.D. THESIS

THEORETIC AND EXPERIMENTAL STUDY OF THE LINEAR TRANSVERSE FLUX RELUCTANCE MOTOR

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The INTRODUCTION presents the general context in which this thesis is elaborated and then presents briefly the chapters of this work. A new structure will be presented here – a linear transverse flux reluctance machine – and each chapter of the thesis deals with a stage in the process of building such a machine and is closed with a part of conclusions.

CHAPTER 1 begins with a comprehensive review of the transverse flux machine. The basic structure and the main rotary and linear prototypes designed and built so far are presented here. The author proposes here a new machine belonging to the above mentioned class – a linear transverse flux machine in two variants. In both cases the machine has a modular structure, the minimum number of modules being 3. First, the hybrid linear transverse flux reluctance was introduced. Its structure can be with one or two permanent magnets on the mobile armature – Figure 1.26. One module of the machine is shown in Figure 1.27.

![Fig. 1.26. The linear transverse flux reluctance machine with permanent magnets](image1)

![Fig. 1.27. A module without the coin of the machine (iron part and permanent magnets)](image2)

To work properly the modules have to be shifted one from each other by $k\tau + \tau/N$, $k \in \mathbb{N}$, where $\tau$ is the tooth pitch and $N$ is the number of the modules. The step of the machine is given by the number of modules at a certain $\tau$. When the command coil is energized, the magnetic flux produced by the coil practically enforces the flux of the permanent magnets through the air-gap, generating in this way tangential and normal forces. Due to the variable reluctance principle the mover will be placed in a position where the teeth of the active module are aligned with those of the stator.

![Fig. 1.30. The linear transverse flux reluctance machine without permanent magnets](image3)

![Fig. 1.31. The linear transverse flux reluctance machine without permanent magnets, with enlarged teeth surface](image4)
Starting from the presented structure, a simpler variant of this machine can be imagined. By eliminating the permanent magnets and the superior iron core we obtain another machine, which behaves exactly like the one presented before, Figure 1.30. An improvement of this machine, which will be proved by FEM analysis, can be brought by enlarging the teeth surface of the machine modules – Figure 1.31.

A new possibility to build the iron core of such a machine is also explored. A variant in which the modules of the machine have the magnetic core made of iron pieces alternating with non-magnetic ones is shown in this chapter.

The fault tolerant character of the presented machines is analyzed here. Many of the ideas expressed for fault tolerant SRM’s can be applied also to this machine.

The final part of first chapter presents a new structure of a transverse flux reluctance machine with linear movement – the tubular variant.

**CHAPTER 2** is focused on the preliminary electromagnetic design of the two proposed structures, with and without permanent magnets. Due to their innovative character it was necessary to elaborate special algorithms in order to design such machines. The two algorithms presented in the thesis differ because the principles at the base of the design procedure are different. In both cases however the given data for beginning the design procedure are the same: the maximum tangential force $F_{t,\text{max}}$, the width of the running track (the stator) $l_s$, the number of machine’s modules $N$, the tooth pitch $\tau$, the air-gap $g$. During the design stages, considering the used materials, various measures from the technical literature will be chosen. Because at each moment the forces are given only by a module, the design procedure will be applied in order to obtain it, all the others modules being exactly the same.

For the machine with permanent magnets on the mobile armature, the basic hypothesis is that the developed tangential and normal forces are due to the flux generated by the permanent magnet. That means that the coil placed on the so called magnetic shunt produces such a flux that it cancels the one through the shunt and directs it through the air-gap. So the starting point in this design procedure is the permanent magnets volume.

By applying the algorithm we obtain the geometrical dimensions of the module’s iron core and permanent magnet. In order to compute the m.m.f. of the used coil we have to create the equivalent magnetic circuit. When designing this machine we presumed that the value of the flux density in the iron core is situated on the linear part of the magnetization characteristic. Using the Kirchhoff laws we can compute it function of the equivalent m.m.f. of the permanent magnets and of the reluctances of the circuit. The coil of this machine can be supplied only in d.c. given the fact that it’s flux must cancel the constant flux of the permanent magnets.

Knowing all the dimensions of the module, consequently the volume of all the components, we can compute it’s mass. So we can obtain a very important characteristic of the machine – the ratio between maximum tangential force and the machine’s mass $F_{t,\text{max}}/m$.

Regarding the linear transverse flux machine without permanent magnets, the starting point of the design procedure is the variation of the magnetic energy in the air-gap for two considered positions. The magnetic energy is expressed function of the flux density in the air-gap and its volume. In this way we could compute the desired geometrical and electrical dimensions. We have to take into account that the estimation of the flux densities for this machine is extremely difficult, and, besides that, it could be possible only for certain tooth pitches. That’s why the variant of adapting the previous algorithm to the case of the machine without permanent magnets seems the best solution.

The design of the machine with enlarged teeth surface is done based also on a theoretical consideration. By increasing the active surface on the iron core $n$ times, the
The equivalent reluctance of the circuit will decrease as many times and, for non-saturated iron cores like the ones considered here, the developed forces will be \( n \) times bigger. So in order to obtain the imposed force we can decrease the m.m.f. of the coil.

The created algorithm was applied here in order to obtain a micro motor for the following given data: maximum tangential force \( F_{\text{max}} = 1N \), width of the running track \( l_c = 20mm \), length of the running track \( L_c = 710mm \), number of modules \( N = 3 \), teeth width \( l_d \) and slots width \( l_c \) is the same \( l_d = l_c = 1mm \), the air-gap that can be practically obtained is 0.3 mm, the slot depth is chosen as half of the tooth pitch, 1 mm.

For both machines the type of material used for the iron core needs to be established. In addition, if we use permanent magnets we need to know their characteristics. Another two important design data are the current density of the coil and the number of module's teeth. Machines with and without permanent magnets, and with enlarged (doubled comparative to the initial one) teeth surface were designed in this thesis using the described algorithm. The value of the m.m.f.'s coil in the first case was computed to be 310 Aturns, while by doubling the teeth surface we could reduce it by \( \sqrt{2} \) times, being 220 A. Regarding the computed masses of a module for the cases mentioned above, they are 165.895 g, 140.8 g, respectively 106.267 g. It can be concluded that the \( F_{\text{max}}/m \) ratio is best for the case with enlarged teeth surface, proposed to be constructed and presented in the Figure 2.13.

**CHAPTER 3** covers the aspects concerning the numerical analysis carried out using FEM. Their purpose is to validate the theoretic design by numeric means, and to obtain various characteristics for which field analysis programs are very useful. The transverse flux machines are characterized by the perpendicular direction of the flux paths on the movement direction. That means the FEM analysis must be done in 3D. The most significant difference from the theoretical hypothesis is the possibility to use in this case the natural magnetization characteristic which is in fact nonlinear, and consequently obtain more accurate results. The performed analysis is focused on two aspects: the flux density distribution in the module and corresponding stator part, and the developed forces. The flux density distribution is presented in three ways: with flux density vector, with flux density map and with graph showing the flux density variation in the air-gap.

The design procedure was applied only for a module. In the numeric analysis at first just one module was analyzed as well, Figure 1.26, but in order to see the influence of the other modules later all of them were considered. The analyzed structures were those designed in the previous chapter. Two positions are particularly interesting: when the teeth of the stator are aligned with those of the mobile armature and the position in which the maximum tangential force is obtained (a shifting between the teeth of 0.5 mm here). Besides these two cases, function of the tooth pitch and the number of modules at each machine, the position...
where the shifting between the two armatures teeth is equal with the positioning step is of real interest.

Another analysis focused on the influence of the magnetic shunt height on the developed forces, both for the machine with and without permanent magnets. The analysis was carried out both for a single module and for all the modules of the machine in order to evidence the influence of the passive modules on the developed forces.

An interesting comparison is obtained by considering various numbers of modules for a machine. In this way the medium tangential force developed by the whole motor is different, so is the positioning step.

The developed forces depend upon three parameters: the air-gap length, the m.m.f. value and the magnetically active cross section of the iron core. The air-gap length is imposed by the technological possibilities, and the m.m.f. value is limited mainly by the saturation of the iron core. In the thesis, the variation of the forces with the air-gap and with the m.m.f. value is presented. In all the situations, having considered that this is a micro motor with non-saturated iron core, the form of variation is hyperbolic. The best solution found to increase the iron core surface was to double the surface of the lower iron core (in the toothed part zone) in order to have a constant cross section in all the parts of the module (fig. 2.13). So keeping the same the value of the m.m.f., we obtain forces twice bigger than in the initial situation. As the purpose stated here was to obtain a machine developing a certain maximum tangential force we could take into account the use of a smaller coil. The numeric analysis allowed us to obtain the static characteristic (tangential and normal forces versus the shifting between the two armatures teeth) taken at the same m.m.f. value of the coil – 220 Aturns.

All the cases studied so far have taken into account just homogenous modules, their iron core being entirely made of magnetic material. But as mentioned before, the core can be made of magnetic pieces alternating with non-magnetic ones. This situation was studied here too.

The final part of the chapter presents a comparison between the theoretic results and the numeric analysis ones. The value of the flux density was in both cases 0.9 T, and the difference between the imposed force and the computed one is of 14%.

**CHAPTER 4** presents the construction of the machine and few experimental results. The iron core of such a machine can be built of steel sheets or soft magnetic composites (SMC). In order to make a comparison a module of both materials mentioned was constructed. The stator of the machine is made of massive iron.
The technological steps that are followed in order to obtain the module are presented extensively in the paper. A comparison between the built modules is made from two points of view: the losses in the iron core and the structure of the modules. Regarding the first mentioned aspect, the losses in the iron core were measured at three different frequencies: 40, 50 and 60 Hz in a similar manner to the no-load operating regime of the transformer. As expected, the steel sheets have the best performances. But concerning the mechanical structure of the modules, the one built of steel sheets has the shortcoming of not having the exact designed dimension – it is a little bit longer due to the possibility of stacking the steel sheets – which can affect the machine functioning. Besides that, the lateral parts must be extended in order to use screws needed for steel sheets stacking. The soft magnetic materials have the great advantage that the structure of the module has very precise dimension and no supplementary technological operations are needed. The two obtained modules are presented in Figure 4.2. As presented in chapter 1 and 3, the module can be built of magnetic pieces alternating with nonmagnetic ones.

The present chapter indicates also solutions for the tubular transverse flux reluctance machine iron core construction. As for the used windings, the ones of the linear variant is very similar to those used in transformers; for the tubular variant two innovative variants of homopolar windings are proposed.

The constructed machine has three modules. They are disposed in an aluminum case, equipped with coolers, in such a way that the shifting between the modules mentioned before is respected. The air-gap can vary between 0.3 and 0.5 mm. The modules are built of steel sheets. The measured mass of the whole machine is 700 g (the supplementary mass comes from the auxiliary components – case, wheels, isolation elements), while the total length is 160 mm. A view of the machine is brought in figure 4.13.

The experimental results were obtained by supplying the machine with direct voltage, in a similar way with a 6/4 SRM. The proposed measurements are related to the developed forces. In order to do this the stator of the machine can be sloped from the horizontal plane, and by solving the forces equation the values of the developed tangential and normal forces will be obtained. The friction coefficient needs to be known in this case. It was determined experimentally, when none of the machine coils is supplied. For this situation this coefficient is \( \mu_f = 0.072 \).

![Figure 4.2. The two constructed modules (the one of steel sheets has lateral screws)](image)

![Figure 4.13. Linear transverse flux reluctance machine.](image)
During the motor’s functioning some aspects were followed. These are related to the variation of the developed forces with the air-gap and the coil’s m.m.f. In this case these variations were obtained only for the normal force due to the great difficulties appeared when measuring the tangential one. This can be said considering the need of a very sensitive sensor, and of the very precise measuring devices (the need of a well controlled movement on distances of tenths of millimeter, high performance dynamometer). Without them, the measurement errors could be so high that the conclusions can be completely mistaken. As well, due to constructive aspects explained previously, the mechanical characteristic of the machine $v = f(F_t)$ becomes strongly affected by the stator and mobile armature teeth irregularities.

For measuring the normal force, the teeth of the two armatures (one module and the stator) were aligned and then the module’s coil was supplied. Then the stator was sloped in such an angle that the motor must be in a position of unstable equilibrium. From the well known equation $F_f = G \cdot \sin \beta$ we can obtain the value of the developed normal force by the machine. This is because in this situation $F_f = \mu (G \cdot \cos \beta + F_{st})$. By knowing the machine mass and the slope we can compute the value of the developed normal force. In order to estimate the tangential force we use a conclusion obtained after the numeric analysis, that the ratio between the maximum tangential force and the normal one is 1/10.

The setup for the force measurement is presented in figure 4.18. The variation of the developed normal force with the air-gap and the m.m.f. was obtained.

Concerning the variation of the normal forces with the air-gap, three values of it were considered, 0.3, 0.4 and 0.5 mm. For the variation of the force with the m.m.f. the same values like in the numeric analysis were considered. For the force computation the slope of the stator regarding the horizontal was computed. The obtained results are presented in figure 4.19 and 4.20.

![Figure 4.18](image-url) Linear three phase machine sloped under a certain angle from the horizontal

![Figure 4.19](image-url) Variation of the measured normal force with the air-gap

![Figure 4.20](image-url) Variation of the measured normal force with the m.m.f.
CHAPTER 5 is dedicated to the presentation of the final conclusions. Each chapter of the thesis has in its final part the corresponding conclusions, in this section these being underlined together with the scientific contributions of the author. Here the most important of them are presented here.

- In the first chapter a detailed state-of-the-art about the transverse flux machines domain is presented. Based on it, two new solutions of transverse flux machines, with and without permanent magnets, of modular type, were proposed here.
- The design algorithms for the two structures were elaborated. The design principle differs in the two cases: for the machine with permanent magnets we start from the volume of the permanent magnet, while in the other case from the variation of air-gap energy. Examples for each case are presented.
- A complex 3D FEM analysis on the designed structures was performed, its results having allowed obtaining the correct dimensions of the machine.
- Different constructive solutions for the iron core and the windings are proposed in this thesis, for each one being determined the losses and shown the advantages and shortcomings. The mentioned solutions regard both types of machine with linear movement: the planar and the tubular motor.
- The experimental measurements have been focused on the tangential and normal forces developed by a module. Due to the resulted irregularities in the mechanical structure of the constructed model, the measurements were realized only for the normal force developed by the machine, besides that the measurement of the tangential force requires high performing measuring devices.

The research presented throughout this paper was approached as well in various papers presented in national and international conferences. It was financially supported by two research grants, the author having received in 2007 the diploma for best paper of one poster session at Linear Drives for Industrial Application LDIA.

Concerning the future researches that can be approached starting from this thesis, the most significant is represented by the tubular transverse flux reluctance machine. It can be considered a variant of the planar motor without permanent magnets presented in this thesis. We underline the fact that the control of this machine is approached here briefly; this aspect could represent as well the subject of other studies.

The thesis has 55 references, on 18 of them the author being a member of the research team. The list of used symbols, of figures and of tables is appended, too.

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